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Note

Complexing capsules—metal extraction and modeling of ion transfer

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Abstract

Polyamide complexing capsules containing a poly(acrylic acid) gel are synthesized by a two steps polymerization process with various diameters (10 μm for μcaps or 200 μm for mcaps). A cationic exchange between gel carboxylic functions and metal ions is realized. Extraction and stripping measurements show that the composition of the capsule membrane does not hinder the mass transfer. A model, taking account only of the diffusion in the gel phase, is studied. © 2002 Published by Elsevier Science B.V.

Keywords: Polyamide complexing capsules; Poly(acrylic acid) gel; Metal extraction; Modeling of ion transfer

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Microencapsulation techniques consist of preparing individualized particles made up of a coating material containing an active matter used in many fields such as medicine, pharmacy, agroalimentary (Benita, 1996). Recently, a new application was developed in the metal extraction field with capsules containing an extractant agent: *complexing capsules* (Asaki et al., 1998). The advantages compared to the liquid–liquid extraction are multiple: faster kinetics of extraction thanks to a larger specific area surface, minimal use of extractant and an easier recovery by filtration or centrifugation process.

In this study, an original process combining two techniques of polymerization in an inverse dispersion (water in oil) is developed. Complexing capsules are obtained in a one pot-two steps reaction. In step one (shell synthesis), an interfacial polycondensation is realized between an aqueous diamine (DA): either ethylenediamine (EDA) or hexamethylenediamine (HMDA) or phenylenediamine (PDA), and an organic solution of acid chlorides: terephtaloyl chloride (DC) and mesoyl chloride (TC). In step two (core synthesis), a radicalar polymerization of a complexing monomer: acrylic acid (AA) partially neutralized with sodium hydrogencarbonate ($\alpha = 0.66$) and a crosslinker: N,N'-methylenebis-acrylamide (MEBA) is initiated with 4,4′-azobis(4-cyanovaleric acid) (ACVA) by increasing the temperature

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(25–65 °C). By changing the nature of the surfactant and the dispersion stirring speed, complexing capsules of different size are synthesized: the complexing minicapsules (PAA-mcaps) (Laguécir et al., 2002a) and the complexing microcapsules (PAA-μcaps) (Laguécir et al., 2002b). The same process is used to synthesize capsules without complexing gel (reference capsules): minicapsules (mcaps) and microcapsules (μcaps).

The morphology of the external polyamide membrane is characterized with SEM photographs. For the two kinds of capsules, the particles are relatively spherical and the membrane surface appears rough with a heterogeneous structure.

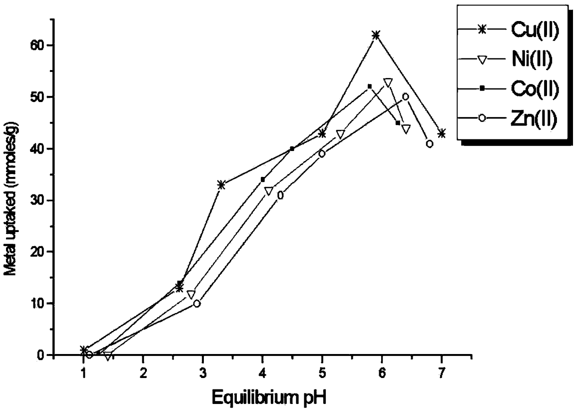

Fig. 1. Effect of the pH of the metallic ion aqueous phase on the various metal extracted by the complexing capsules. Metal uptake (mmol/g) vs. equilibrium pH.

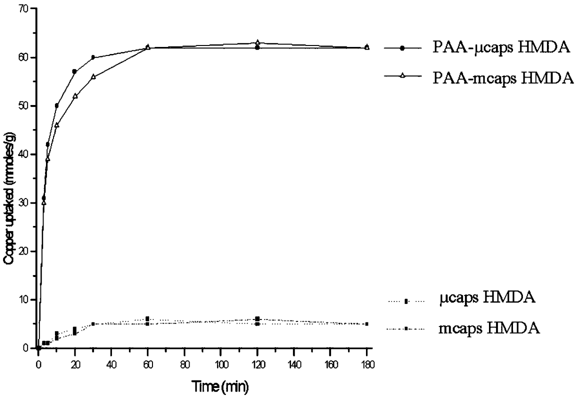

Fig. 2. Effect of the capsule size on the extraction kinetics of copper. Copper uptake (mmol/g) vs. time (min).

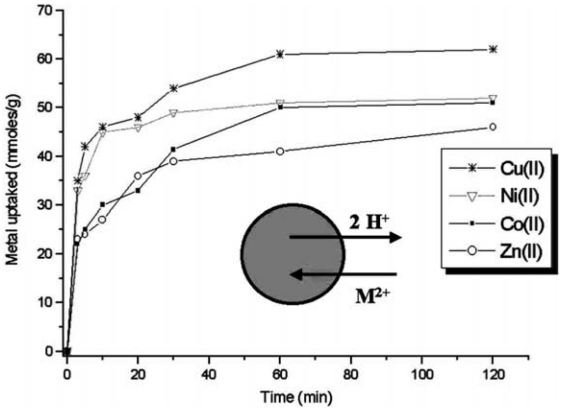

Fig. 3. Extraction kinetics of various metallic ions. Metal uptake (mmol/g) vs. time (min).

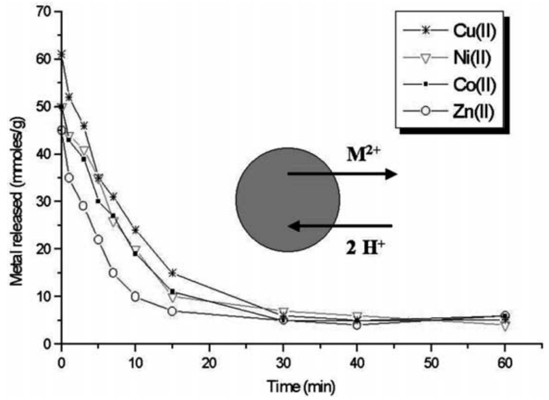

Fig. 4. Stripping kinetics of various metallic ions. Metal released (mmol/g) vs. time (min).

The capsules diameters are measured by a laser diffraction particle size distribution apparatus. The average diameters (from the granulometric curves) are respectively: 220 μm for PAA-mcaps and 210 μm for mcaps; 10 μm for PAA-μcaps and 12 μm for μcaps.

The content of encapsulated polyacrylic acid is determined with pHmetric titrations. The capacity (number of mmol of carboxylic function per gram of wet capsules) is: 0.15 meq/g for PAA-mcaps and 0.20 meq/g for PAA-μcaps. The capsule size has no evident effect on the radicalar polymerization yield of AA.

The capacity against metallic ions is determined with complexation measurements. A given amount of capsules are shaken with a well-known concentration solution of the studied metallic ion. After the optimal time for reaching the extraction equilibrium, the capsules are recovered either by filtration for minicapsules or by centrifugation for microcapsules and the residual metallic ion concentration is checked. All metallic ion concentrations are determined by atomic absorption.

The extraction experiments are carried out with various metallic ions (Cu(II), Ni(II), Co(II) and Zn(II)) in buffered pH solution and at a constant ionic strength (Fig. 1). For the four studied metallic ions, we notice a maximum of complexation around pH 6. In all following extraction experiments, the aqueous solution is buffered to pH 6.

The extraction kinetics curves are nearly the same for mini and microcapsules (Fig. 2), so all following experiments are done with minicapsules, and for the four metallic ions (Fig. 3) the shape is the same. The maximum of extraction is reached after 1 h.

After the extraction experiments, the complexed capsules are shaken with hydrochloric solutions and the metallic ion release is determined. The stripping kinetics curves (Fig. 4) are almost the same for the four studied metallic ions.

The extraction kinetics curves of complexing capsules synthesized with various experimental conditions show that the polyamide nature

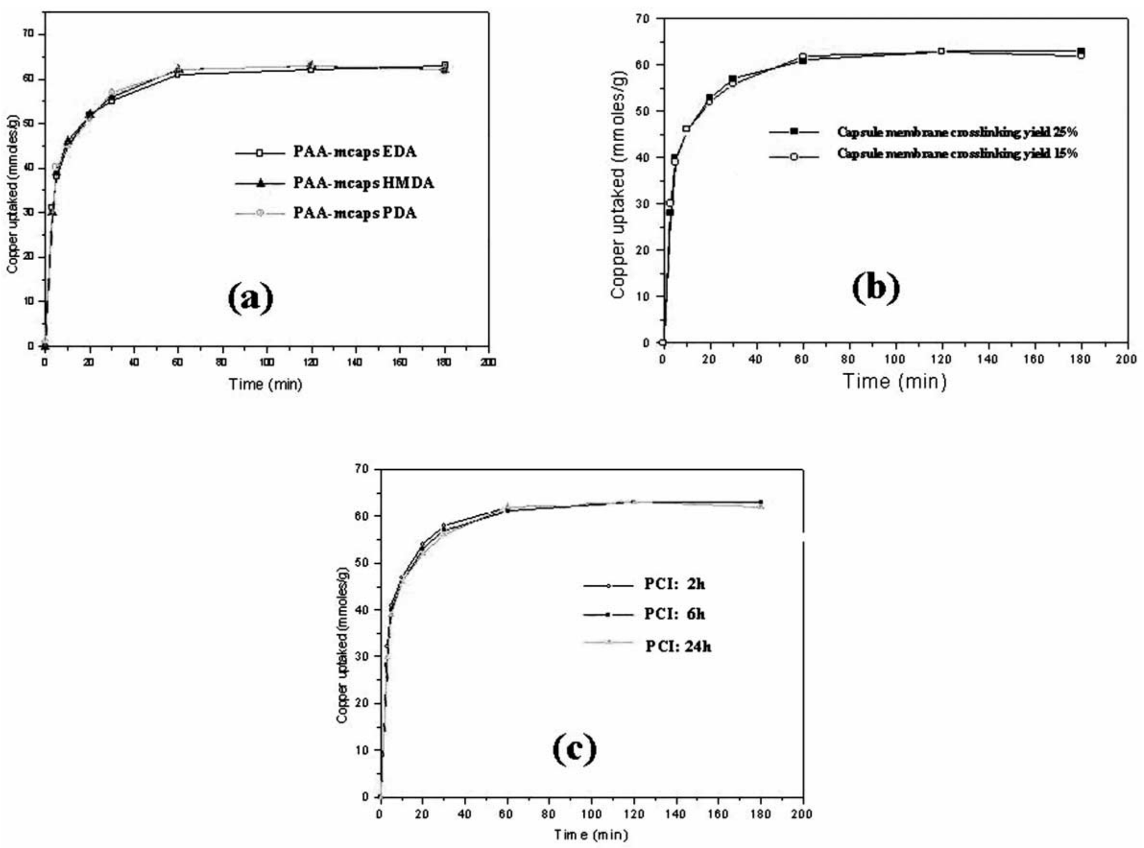

Fig. 5. (a) Effect of the polyamide nature of the capsule membrane on the extraction kinetics of copper. Copper uptake (mmol/g) vs. time (min). (b) Effect of the crosslinking yield of the capsule membrane on the extraction kinetics of copper. Copper uptake (mmol/g) vs. time (min). (c) Effect of the thickness of the capsule membrane on the extraction kinetics of copper. Copper uptake (mmol/g) vs. time (min).

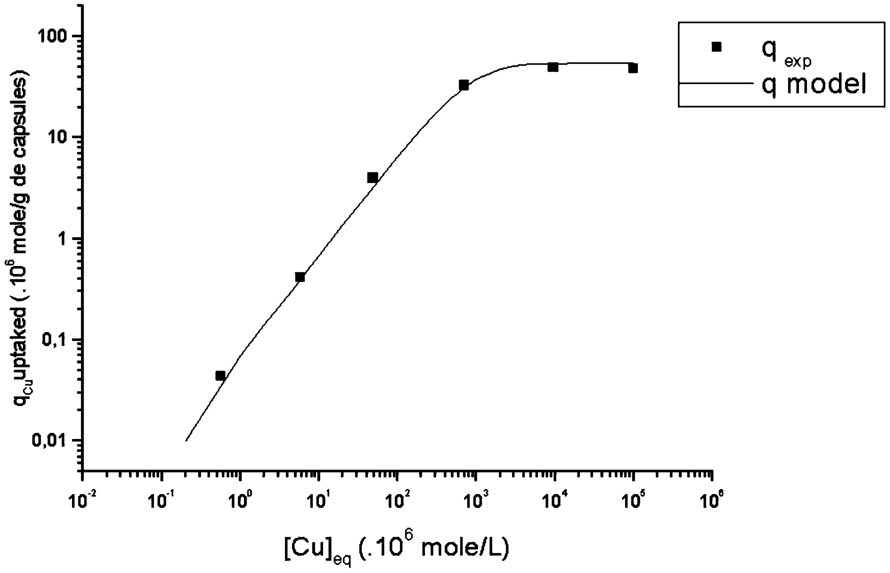

Fig. 6. Distribution isotherm in the copper extraction. Q (10^6 mol/g of capsules) vs. $[Cu]_{\text{fluid phase}}$ (10^6 mol/l).

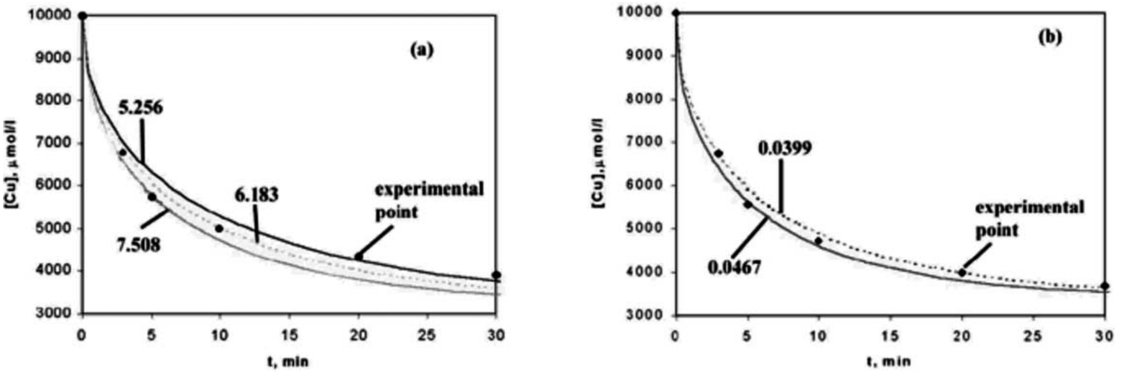

Fig. 7. (a) Copper transfer kinetics into mcaps. $[Cu]_{\text{fluid phase}}$ (µmol/l) vs. time (min). (b) Copper transfer kinetics into µcaps. $[Cu]_{\text{fluid phase}}$ (µmol/l) vs. time (min).

(Fig. 5a), the membrane crosslinking yield (Fig. 5b) and the membrane thickness (Fig. 5c) do not influence the kinetics. The membrane thickness is assumed to be linked to the polycondensation reaction time (Poncelet et al., 1990; Janssen and Te Nijenhuis, 1992; Janssen et al., 1993).

The equilibrium distribution between the fluid and solid phases in an ion exchange process is generally described by a mass action law type equation. This equation should be written in terms of activities, but since the activity of the ions in the solid is difficult if possible to calculate, concentrations were used instead. Since a large excess of sodium nitrate was used during the batch experiments conducted to determine equilibrium data, the gel was supposed to be initially in the sodium form, and the exchange between copper and sodium ions was considered. Based on the stoichiometry of the exchange process and taking into account the conservation of total concentrations both in the solid and in the fluid phases, the following dimensionless equilibrium constant (selectivity coefficient) is obtained:

$$K_{\mathrm{Cu}}^{\mathrm{Na}} = \frac{y_{\mathrm{N}}^{2} x_{\mathrm{C}}}{y_{\mathrm{C}} x_{\mathrm{N}}^{2}} = \frac{\left(\dfrac{Q-2q}{Q}\right)^{2} \dfrac{2c_{\mathrm{C}}}{c_{\mathrm{T}}}}{\dfrac{2q}{Q}\left(\dfrac{c_{\mathrm{N}}}{c_{\mathrm{T}}}\right)^{2}}$$

where x and y are the equivalent fractions and c and q being the concentrations in the fluid and solid (gel) phases, respectively (subscript N and C refer to sodium and copper respectively, q is the copper concentration). An optimization procedure with the experimental data, at pH 6 and $[\mathrm{NaNO_3}] = 0.01$ M enables the calculation of the total exchange capacity $Q = 139.8$ μmol/g and of the selectivity coefficient $K_{\mathrm{Cu}}^{\mathrm{Na}} = 1.363 \times 10^{-2}$. In Fig. 6 the theoretical curve and the experimental points are plotted showing that the mass action law describes reasonably the equilibrium in this system. The kinetics was described by the Nernst–Planck equation, which takes into account both the concentration (activity) and the electrical gradients. Mass balances to the batch adsorber and inside the gel phase of the particles, where the fluxes are described by the Nernst–Planck model, after some manipulations, give a partial differential equation in two independent variables: the radial position in the gel and time. This equation with its initial and boundary conditions was solved by the method of lines, using an orthogonal collocation in finite elements method for the discretization of the radial coordinate along the gel and a stiff integrator for the solution of the remaining initial value problem. The best value for the effective diffusivity inside the gel phase is then searched by comparison between the model solution and the experimental values. Apparently, the best value depends on the particle dimension since different effective diffusivities were obtained for the mini and microcapsules: minicapsules, $D_{\mathrm{eff\ Cu}}$ (mean value) $= 6.31 \times 10^{-10}$ cm^2/s; microcapsules $D_{\mathrm{eff\ Cu}}$ (mean value) $= 0.043 \times 10^{-10}$ cm^2/s) (Fig. 7a,b).

In conclusion, we have developed a new technique for the synthesis of complexing capsules containing a polyacrylic acid gel and of reference capsules without active matter. Their ability of metal complexation and release were also investigated. The influence of various synthesis parameters and experimental conditions were highlighted. The capsule membrane has no significant effect on the complexing properties. The modeling of the mass transfer of ionic species during the extraction process shows a significant size effect on the transfer dynamics.

References

Asaki, M., Ichinose, T., Monjushiroh, H., Fukumoto, T., Watarai, H., 1998. Polyamide microcapsules containing alginic acid: extrability of metal ions and surface characterization by XPS. J. Microencapsulation 15, 453–463.

Benita, S., 1996. Microencapsulation: Method and Industrial Applications. Marcel Dekker, New York.

Janssen, L.J.J.M., Te Nijenhuis, K., 1992. Encapsulation by interfacial polycondensation. II. The membrane wall structure and the rate of the wall growth. J. Membr. Sci. 65, 69–75.

Janssen, L.J.J.M., Boersma, A., Te Nijenhuis, K., 1993. Encapsulation by interfacial polycondensation. III. Microencapsulation; the influence of process conditions of wall permeability. J. Membr. Sci. 79, 11–26.

Laguécir, A., Ernst, B., Frère, Y., Danicher, L., Burgard, M., 2002a. Extraction of metal cations by polyterephtalamide capsules containing a poly(acrylic acid) gel. J. Microencapsulation 19, 17–28.

Laguécir, A., Frère, Y., Danicher, L., Burgard, M., 2002. Size effect of complexing microcapsules on copper ion extraction. Eur. Polym. J. to be published.

Poncelet, D., Poncelet De Smet, B., Neufeld, R.J., 1990. Nylon membrane formation in biocatalyst microencapsulation: physicochemical modeling. J. Membr. Sci. 50, 249–267.